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Letter

Discussion on Spatial and Time Averaging Restrictions Within the Electromagnetic Exposure Safety Framework in the Frequency Range Above 6 GHz for Pulsed and Localized Exposures

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Both the current and newly proposed safety guidelines for local human exposure to millimeter-wave frequencies aim at restricting the maximum local temperature increase in the skin to prevent tissue damage. In this study, we show that the application of the current and proposed limits for pulsed fields can lead to a temperature increase of 10°C for short pulses and frequencies between 6 and 30 GHz. We also show that the proposed averaging area of 4 cm^2, that is greatly reduced compared with the current limits, does not prevent high-temperature increases in the case of narrow beams. A realistic Gaussian beam profile with a 1 mm radius can result in a temperature increase about 10 times higher than the 0.4°C increase the same averaged power density would produce for a plane wave. In the case of pulsed narrow beams, the values for the time and spatial-averaged power density allowed by the proposed new guidelines could result in extreme temperature increases. Bioelectromagnetics. 2020;41:164–168.

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Exposure safety frameworks have been proposed for continuous and pulsed electromagnetic fields (EMFs) at frequencies above 6 GHz in previous and current safety standards [IEEE, 2005, 2019], as well as in current exposure limiting guidelines [ICNIRP, 1998] and in their proposed revision [ICNIRP, 2018]. Major modifications of the guidelines became necessary as frequencies above 6 GHz will be applied in new emerging handheld and/or body-mounted consumer devices, e.g. devices of the fifth-generation cellular network technology (5G) or radiative wireless power transfer systems. These systems may operate in the extreme near-field, resulting in highly localized exposures. Furthermore, they can be highly broadband which can reduce the minimal data transmission (i.e. burst or pulse) durations from 10 ms (supported by 4G) to 1 ms (5G) or less [Qualcomm, 2016]. It is evident that this is just the beginning of exploring these new frequency bands for a wide range of applications.

In addition to modifying the incident power density (PD) limits, new dosimetric limits have been defined, namely the transmitted PD (S_{tr}) [ICNIRP, 2018] and dosimetric reference limits (DRL) [IEEE, 2019]. The corresponding restrictions for the general public are summarized in Table 1 for frequencies between 6 and 100 GHz. In this letter, we look at limits, such as those currently proposed or recently approved for the revised ICNIRP guidelines and IEEE standard, and investigate whether such limits are consistent with the stated goals of the exposure safety frameworks of preventing excessive heating in the case of pulsed and/or localized radiation. In cases when they are not consistent, we discuss how consistency can be achieved. In line with the

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TABLE 1. Basic Restrictions for the General Public and Uncontrolled Environment in the Frequency Range 6–100 GHz in the Current (Active) and Draft Standards/Exposure Guidelines

	Frequency f (GHz)	Restricted quantity	Limit value	Spatial averaging	Averaging time (min)
ICNIRP (1998)					
Continuous	6–10	SAR	2 W/kg (head, trunk) 4 W/kg (limbs)	10 g	6
	10–100	S_{inc}	10 W/m^2	20 cm^2	$68/f^{1.15}$
	10–100	S_{inc}	200 W/m^2	1 cm^2	$68/f^{1.15}$
Pulsed	$f = 1/\tau_p$		basic restriction applied for f		
	6–10	SA	2 mJ/kg (head)	10 g	
IEEE (2005)					
Continuous	6–30	S_{inc}	10 W/m^2	$100\lambda^2$	$150/f$
	30–100	S_{inc}	10 W/m^2	100 cm^2	$25.24/f^{0.476}$
	30–100	S_{inc}	100 W/m^2	1 cm^2	$25.24/f^{0.476}$
Pulsed	6–100	E_{peak}	100 kV/m		
	6–100	S_{peak}	$\sum_0^{0.1\text{s}}\left(S_{i,\text{peak}} \times \tau_i\right) \le \frac{MPE_{\text{avg}} \times t_{\text{avg}}}{5}$		
ICNIRP (2018)					
$t_{exposure} \geq 6$ min	6–30	S_{tr}	20 W/m^2	4 cm^2	6
	30–100	S_{tr}	20 W/m^2	1 cm^2	6
$t_{exposure} < 6$ min	6–30	H_{tr}	$0.5 + 0.354\sqrt{t-1}$ kJ/m^2	4 cm^2	
	30–100	H_{tr}	$0.5 + 0.354\sqrt{t-1}$ kJ/m^2	1 cm^2	
IEEE (2019)					
	6–100	$S_{epithelial}$	20 W/m^2	4 cm^2	6
	30–100	$S_{epithelial}$	40 W/m^2	1 cm^2 (if exposed area <1 cm^2)	6

E_{peak} = peak (temporal) electric field intensity; H_{tr} = transmitted energy density; SA = specific absorption; SAR = specific absorption rate; $S_{epithelial}$ = epithelial energy density; S_{inc} = incident power density; S_{peak} = peak (temporal) power density; S_{tr} = transmitted power density.

abovementioned safety standards and exposure guidelines, the presented analysis focuses exclusively on the magnitude of the tissue temperature increase as a risk factor and does not consider other aspects, such as the thermoelastic effect related to the rapidity of temperature increase.

In IEEE [2019] it is stated that, for pulsed exposure to frequencies below 30 GHz, compliance requires that during any 100 ms of the exposure

$$\sum_{i=1}^{n} (S_{i,\text{peak}} \times \tau_i) \le \frac{ERL_{\text{local}} \times t_{\text{avg}}}{5} \tag{1}$$

where $S_{i,\text{peak}}$ is the temporal peak PD (W/m^2) of the ith pulse (in a train of n pulses), τ_i is the pulse width (s), $t_{\text{avg}} = 6$ min is the averaging time, and ERL_{local} is the exposure reference level (ERL) for local exposure (given in table 11 of IEEE [2019] for frequencies >6 GHz). This is equivalent to limiting the transmitted energy density (fluence) within 100 ms to a fifth of the one allowed during the entire 6-min averaging time. Consequently, a maximum of five such pulses is permitted within any period equal to the averaging time. It is crucial to highlight that pulse-duration-independent limits on fluence (equivalent to limits on averaged PD in a given time interval) do not constrain the peak-to-average ratio (or the peak) of the exposure. Following the approach in IEEE [2019] for deriving the DRL and ERLs for frequencies ≥6 GHz, which uses equation (3a) and the tissue parameters in Foster et al. [2017], the maximum surface temperature can be calculated according to:

$$\Delta T_s = \frac{S_{\text{tr}} \times R_1}{k} \text{erf}\left(\sqrt{\frac{t}{\tau_1}}\right) \tag{2}$$

where S_{tr} is the transmitted PD (W/m^2), R_1 is the characteristic heating length from a point source (m) equivalent to the quantity given by Equation (4) and defined as the intrinsic distance scale in Equation (1) of Foster et al. [2017], τ_1 is the thermal time constant (s), k is the thermal conductivity (W/K/m), and erf() is the error function. Equation (2) is the step-response function for the 1D bioheat transfer equation (BHTE) in an adiabatic half-space of tissue subject to surface heating. Pulsed heating can be computed by adding and subtracting time-shifted step-response functions [Neufeld and Kuster, 2018]. The surface heating approximation breaks down when the penetration depth is non-negligible or the pulse duration is extremely short. The applicability of this theoretical approximation, its assumptions and limitations, are discussed in detail in Neufeld and Kuster [2018] and Neufeld and Kuster [2019]. At 100 GHz, the surface heating approximation breaks down around 30 ms, and below 30 ms, the approximation

$$\Delta T_s = S_{\mathrm{tr}} t / (\rho_t c L)$$

is more accurate (ρ_t is the tissue density (kg/m^3); c is the heat capacity (J/kg/K); L is the power penetration depth (m)).

In all subsequent temperature increase evaluations, it is assumed that the transmitted PD is set at a 6-min-averaged value of 20 W/m^2, in accordance with the limits [ICNIRP, 2018; IEEE, 2019] for the general public (limits for occupational exposure are higher, i.e. 100 W/m^2 in IEEE [2019]).

CONTINUOUS EXPOSURE

The steady-state temperature increase for continuous plane wave exposure according to IEEE [2018], i.e. using the suggested values of $R_1 = 7$ mm, $\tau_1 = 500$ s, and $k = 0.37$ W/K/m, would be 0.4°C.

SINGLE-PULSE EXPOSURE

However, if one assumes a single pulse of 100 ms carrying one-fifth of the transmitted energy density allowed within the 6-min averaging period, as Equation (1) foresees, then the temperature increase reached at the end of the exposure would be about 4.4°C. Considering the finite penetration depth—experimentally found to vary within the range of 0.05–0.2 mm at 94 GHz, according to figure 4 in Walters et al. [2000]—and a readily occurring transmission coefficient of 0.9 [Samaras and Kuster, 2019], this results in a reduced temperature increase prediction of 1.4–2.8°C. This is in line with the temperature measurements from Walters et al. [2000], which provide a temperature increase of 1.5°C when scaling their experimentally fitted function to a transmission coefficient of 0.9. Even higher transmission coefficients can result from oblique incidence or different skin layer thicknesses [Samaras and Kuster, 2019].

TRAIN OF PULSES

The repetition of five consecutive pulses, complying with Equation (1), at the beginning of each 6-min averaging period for an exposure of two h, can lead to a temperature increase of 9.9°C.

THERMAL TIME CONSTANT

Temperature rise according to Foster et al. [2017] is dependent on the thermal time constant τ_1 of the model. In the above calculations, we used a value of 500 s [Foster et al., 2017], as suggested by the newly approved standard [IEEE, 2019]. However, for local exposure, this time constant may take values as small as 100 s [Morimoto et al., 2017], resulting in a roughly twofold increase of the maximum temperature increase of the same pulse width.

INTENSE PULSES IN THE MILLIMETER-WAVE FREQUENCY RANGE (30–300 GHz)

In the approved standard IEEE [2019] and for frequencies above 30 GHz, when the pulses are of less than 10 s duration and separated by a few tens of seconds, they are subject to one more limitation, i.e. that the incident energy density of every pulse shall be limited to less than 0.2 $\tau^{1/2}$ kJ/m^2 for persons in unrestricted environments (τ is the duration of the pulse). Using the same approach, it can be shown that this limitation can keep the maximum surface temperature increase to less than 1°C. This is more conservative in comparison to the old standard [IEEE, 2005].

NARROW IRRADIATED AREAS

Assuming an incident beam with a Gaussian profile of radius w and peak PD of P_p, the resulting steady-state peak temperature increase becomes, according to Neufeld et al. [2018],

$$T_p = F_T P_p \frac{w}{k} \sqrt{\frac{\pi}{2}} e^{\frac{w^2}{2l^2}} \left(1 - \mathrm{erf}\left(\frac{w}{\sqrt{2}\, l}\right)\right) \tag{3}$$

where F_T is the power transmittance to the tissue and l is the characteristic heating length (m) of the BHTE for a point source [Yeung and Atalar, 2001]:

$$l = \sqrt{\frac{k}{\rho_t \rho_b c_b M_b}} \tag{4}$$

where ρ_t and ρ_b are tissue and blood mass density (kg/m^2), c_b is the heat capacity of blood (J/kg/K), M_b is the volumetric flow rate of blood per unit mass of tissue (ml/min/kg), and k is the thermal conductivity of tissue (W/k/m); $l \approx 7$ mm for a blood perfusion rate of the skin of 102 ml/min/kg (equivalent to R_1 in Equation (2)). If we assume an averaging area of 4 cm^2 and an incident Gaussian beam of 1 mm radius [Neufeld et al., 2018], the maximum temperature increase can reach 3.9°C while the plane wave exposure would have produced an increase of only 0.4°C (Fig. 1). Highly localized exposures occur in close proximity to antenna elements (e.g. the exposure radius near the dipole array and slot antenna array validation sources defined in the latest draft of the IEC/IEEE 63195 [2018] PD measurement standard varies in the range of 0.4–2 mm at 30–90 GHz). For smaller antennas or near metallic edges, the radius can even be smaller. The maximum temperature increase resulting from such a narrow-irradiated area could be limited to less than 1°C (a temperature rise limit discussed in ICNIRP [1998]; IEEE [2005]; IEEE [2019]) if an averaging area of 1 cm^2 was used. For continuous exposure, the radius would have to increase to more than 3.2 mm to limit the increase to less than 1°C.

BLOOD PERFUSION

The peak temperature, the thermal time constant (τ_1 in Foster et al. [2017] and in IEEE [2019]), and the characteristic thermal length l (R_1 in Foster et al. [2017] and in IEEE [2019]) are all dependent on blood perfusion. It has been shown that as the epidermis is not perfused, an effective value of 30 ml/min/kg for blood perfusion should be applied in the model for frequencies > 15 GHz [Neufeld et al., 2018]. This has only a small impact on the peak temperature increase

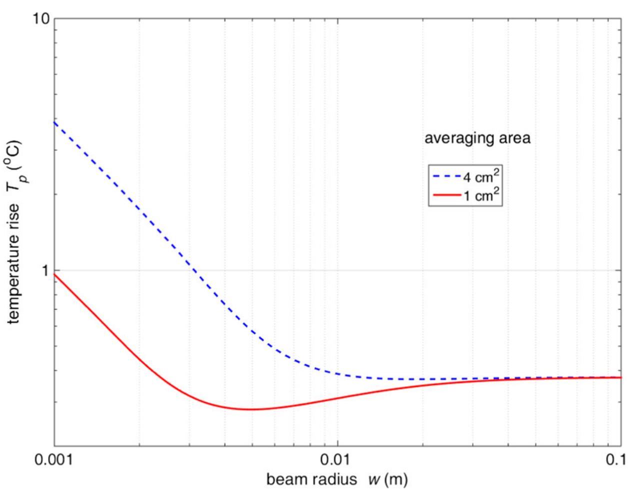

Fig. 1. Maximum surface temperature increase normalized to plane wave temperature rise as a function of the beam width for continuous exposure and an averaging area of either 1 or 4 cm^2.

of the narrow beam of 1 mm radius, i.e. 4.1°C instead of the previously mentioned 3.9°C (using an averaging area of 4 cm^2). However, the lower blood perfusion rate will substantially affect the plane wave maximum temperature increase, which will rise by almost twofold from 0.4 to 0.7°C.

PULSED EXPOSURE AND NARROW IRRADIATED AREAS (6–30 GHz)

When we combine the above considerations and compute numerically, using the 4D Green's function [Yeung and Atalar, 2001], the maximum temperature increase for a narrow irradiated area of 1 mm radius applied in five consecutive pulses of 100 ms width complying with (1), we obtain a peak temperature increase of several 100°C after 500 ms of exposure. Although the model is not valid for such temperature increases (because, e.g. coagulation, evaporation, and charring would long have occurred, and also because of the simplified assumption of surface energy deposition), the extreme magnitude of these results shows that exposure conditions may occur for which the temperature increase cannot be considered safe. Also, the temperature increase rate (initially $S_{tr}/(\rho_t c\ L)$ for a plane-wave with penetration depth L), could lead to thermoelastic effects [Lin and Wang, 2007; Elder and Chou, 2003].

INTENSE PULSES AND ICNIRP FLUENCE LIMITS

Similar to the approach of IEEE [2019] for pulsed EMF > 30 GHz, the guidelines of ICNIRP [2018] restrict the transmitted energy density (fluence) to the body for all frequencies above 6 GHz and short exposures. However, ICNIRP [2018] sets the transmitted energy density limit to a constant value for exposures shorter than 1 s, which allows for ultra-short pulses to reach arbitrarily high-PDs. A single plane-wave pulse of 10 ms carrying the maximally ICNIRP-allowed transmitted energy density of 0.5 kJ/m^2 (Table 1) can result in a surface temperature increase of 2°C (much higher for localized exposure—see above).

CONCLUSION

In conclusion, the results presented above demonstrate that, in the case of very short pulses, pulse-duration-independent limits imposed on transmitted energy density (fluence) alone cannot preclude the induction of high-temperature increases in the skin. Pulse-duration-dependent limits should be applied also for pulses less than 1 s and possibly less than 30 GHz as well. Even though the amplifiers of the currently developed consumer devices will not allow the full exploitation of the limits of the guidelines, the guidelines should not implicitly rely on this, as they will be used to develop exposure assessment standards with the aim of ensuring safety of any future technology, e.g. IEC/IEEE 63195 [2018]. Accordingly, either assumption must be explicitly stated in the guidelines, or the limits should be adapted to be intrinsically safe. In the absence of limitations applied to the peak-to-average power ratio of pulses, it is possible to deliver to the body large amounts of energy within a very short time interval. For millimeter-wave frequencies, where the absorption is superficial, this results in fast and dramatic temperature rises, as the step response function is proportional to the rapidly rising $\mathrm{erf}\,(\sqrt{t/\tau_1})$ rather than the $(1 - e^{-t/\tau_1})$ commonly encountered for deeper heating. As far as spatial averaging is concerned, it has been shown that an averaging area smaller than 4 cm^2 should be introduced in order to avoid peak PDs in narrow beams [Neufeld and Kuster, 2018] that overheat the tissues. With increasing beam radius, e.g. at larger distances from the antenna(s), the tolerable averaging area increases rapidly, provided that there are no sharp exposure peaks. Duration-independent limits on the fluence of pulses are not suitable. They should either be replaced by duration-dependent fluence limits for pulses or by limits on the (temporal) peak exposure. In both cases, the limits should be set after taking narrow-beam exposures into consideration. These limits will depend on the chosen spatial and temporal averaging schemes and the maximum temperature increase deemed acceptable. Forward-looking knowledge about the technical needs and priorities of the industry could allow for selecting the balance between thresholds (averaging time and area, peak-to-average ratio, PD) to minimally impact the technological potential using the same limit-setting framework.

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